Observation of NLIW in the South China Sea using PIES

David M. Farmer
Graduate School of Oceanography (educational)
University of Rhode Island
Narragansett, RI 02882
Phone: (401) 874-6222 fax (401) 874-6889 email: dfarmer@gso.uri.edu

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LONG-TERM GOALS

To study the mechanisms of generation, evolution and propagation of high frequency nonlinear internal waves [NLIW] in the vicinity and west of Luzon Strait in the South China Sea, making use of pressure equipped inverted echo sounders.

OBJECTIVES

Our objectives are (1) to observe the internal tide propagating west of Luzon Strait and its progressive evolution in shape and speed as it traverses the South China Sea under the influence of nonlinearity, non-hydrostatic effects, rotation, topography, currents and stratification, and (2) to interpret the results with the help of models that incorporate these effects.

APPROACH

Our approach involved deployment of three modified pressure equipped inverted echo-sounders [PIES], set up to transmit every 6s. These instruments measure the return acoustic travel time from sea-floor to surface, which is modified by variations in the local stratification resulting from passage of internal waves. Knowledge of the background stratification is provided by CTD casts. Time series measurements of the acoustic travel time then provide a basis for inferring the first mode internal response. Nonlinear non-hydrostatic models can be used to interpret the evolution of the waves as they pass successive measurement sites. Additional modeling is used to simulate the generation of the internal tide measured within Luzon Strait.

WORK COMPLETED

The field program was successfully completed, with data from three instruments acquired from April to October in 2007. The results are being interpreted in terms of:

1.   A model of the inverted echo-sounder instrument performance;

2.   A two-layer weakly nonlinear wave evolution theory (Ostrovsky, 1978);

3.   A two-layer weakly nonlinear model for generation and evolution (Gerkema, 1996);

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4.   A linear generation model (Hibya, 1986) coupled to a fully nonlinear evolution model (Helfrich, 2007).

At this time (1) has resulted in the publication Li et al. (2009) and (2) and (3) have resulted in the publication Farmer et al. (2009). The combined model (4) has been carried out by student Li Qiang and is being incorporated in his PhD thesis for subsequent publication. Li Qiang is also looking at related effects associated with influence of the Kuroshio on the generations process under the IWISE program. Key individuals involved in the NLIWI project include PhD student Li Qiang (URI), Erran Sousa (URI), responsible for technical aspects of deployments and recovery, Jae-Hun Park (URI) for assistance in implementing models, Tim Duda (WHOI) for input on modeling acoustical scattering from rough surfaces and Karl Helfrich (WHOI) for helpful discussions on model analysis.

RESULTS

1.   Our model analysis of the inverted echo sounder successfully described instrument performance across a range of wind and sea-state conditions. Specifically the role of a wind speed dependent rough sea surface in contributing to acoustic travel time scatter was evaluated, together with the contribution of ambient noise was evaluated and shown to be consistent with our observations. The results provide quantitative information on a modest wind speed dependent bias in travel time estimates and explain the statistical distribution of scatter, the latter motivating a self-consistent approach to data analysis. The inversion of the time series to recover internal wave information was evaluated using the DJL model and comparisons to co-located temperature measurements acquired by Steve Ramp (NPS/MBARI).

2.   Ostrovky's (1978) weakly nonlinear 2-layer rotational theory together with Boyd's (2005) nonlinear stability analysis provided an initial basis for interpreting results of field observations in the South China Sea. The theory evaluates wave evolution in the context of rotational dispersion and nonlinear steepening. The stability analysis illustrates the way in which nonlinearity tends to dominate for the semi-diurnal internal tide across the deep basin of the South China Sea, whereas rotation effectively inhibits steepening of the diurnal component. In practice, since the tides are mixed, it is more appropriate to cast the stability problem in terms of local interfacial slope. The theory appears to account for key features of the observations such as illustrated in Fig. 1, including the delayed appearance of high frequency nonlinear waves west of Luzon Strait.
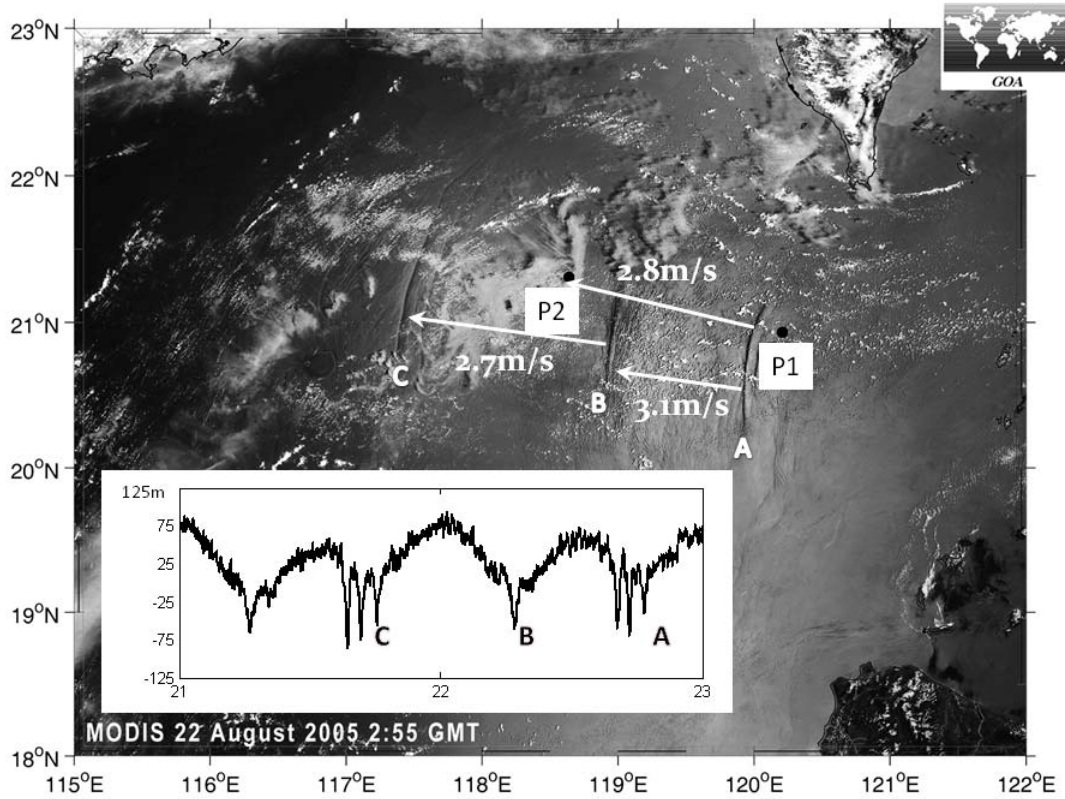
Fig. 1: MODIS image showing 3 nonlinear internal wave trains crossing the deep basin west of Luzon Strait. Inset: Corresponding inverted echo sounder time series for these waves at P2 from which path-averaged wave speeds are determined. Note alternating pattern of waves. (Image adapted from that provided byf C. Jackson (GOA).

3. Gerkema's (1996) weakly nonlinear 2-layer rotational model allows us to incorporate topography and include internal tide generation. The model was implemented with two ridges in Luzon Strait and illustrates features of the generation and wave evolution, specifically the alternating pattern of high frequency nonlinear wave evolution that occurs during part of the fortnightly cycle. The model provides a convenient basis for evaluating the role of rotational dispersion which is clearly illustrated by successive runs with and without rotation. Rotational dispersion plays a major role in modifying the diurnal internal tide in the South China Sea, but has relatively less effect on the semi-diurnal tide (Figs 2, 3).
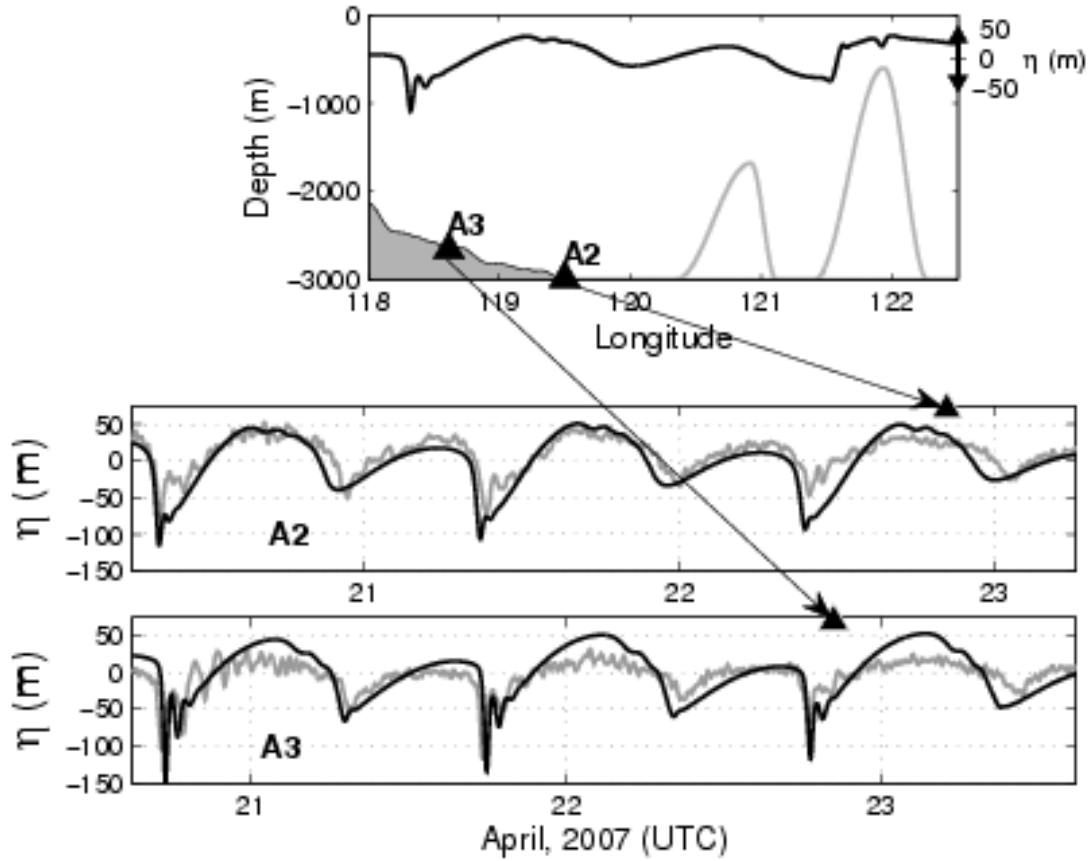
Fig. 2: Top panel: Two-layer model (Gerkema, 1996) calculation of interface displacements along path of inverted echo-sounder deployments for period identified in Fig. 1. Model is driven by TPXO predictions; smoothed representations of actual topography are used. Lower panel: Inverted echo sounder time series (black)acquired at locations A2, A3 shown in top panel, superimposed on modeled time series (grey). Time series displaced to offset the propagation time between instruments.
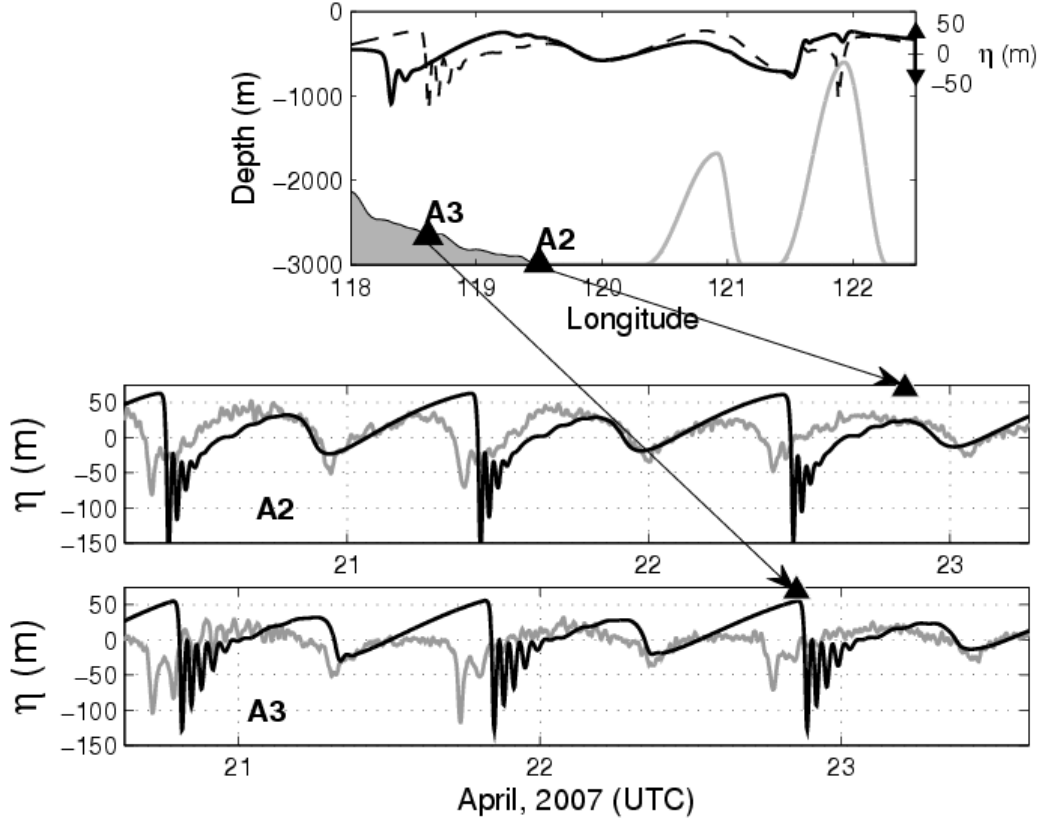
Fig. 3: Top panel: Modeled interface displacements with (solid line) and without (dashed line) rotation. Lower panels: Observed time series (solid line) and modeled time series without rotation (dashed line).

4.   The fact that our measurements of the internal tide between the two ridges shows little sign of nonlinear modification such as steepening or high frequency nonlinear wave development suggests that a linear theory may provide a reasonable representation of the generation process. We used Hibya's (1986) two-layer model driven with TPXO tidal predictions. With internal tidal generation at both ridges the model produces results consistent with observations at our easternmost mooring station A1 in the middle of Luzon strait. Notwithstanding the simplifications the results provide a reasonable basis for generating initial conditions with which to drive Helfrich's (2007) 2-layer fully nonlinear rotational wave evolution model. Predictions carried out by PhD student Li Qiang show general consistency with our observations.

5.   High frequency nonlinear internal waves are less often seen during winter months and are much diminished or not seen at all in remote sensing images east of Luzon Strait at any time of year. It has been proposed Karl Helfrich, WHOI, pers. comm.) that diminished signals east of the strait can be explained by the deeper stratification to east of Luzon, due to the Kuroshio. It might also be expected that the seasonal intrusion of the Kuroshio would also impact the generation process. The dependence of internal tide generation and consequent evolution of nonlinear internal wave trains are being examined with the MITgcm under the IWISE and interpreted in terms of remotely sensed characteristics of the Kuroshio and our inverted echo-sounder measurements.

IMPACT/APPLICATIONS

Interpretation of the inverted echo-sounder observations using a sequence of models of graduated complexity provides a framework for identifying the mechanisms by which the well defined high frequency nonlinear internal wave trains are generated and providing a predictive capability. Our results to date, evaluated at a latitude of 21.3N are consistent with the generation of a large amplitude internal tide over the eastern ridge, together with a modest contribution from the western ridge, that evolves under the combined influence of rotation and nonlinearity as it propagates across the deep basin of the South China Sea. Rotational dispersion inhibits steepening of the diurnal internal tide while nonlinear effects dominate evolution of the semi-diurnal signal, accounting for the observed systematic alternation in character of nonlinear internal waves in the deep basin (Figs. 2, 3). Observations at our station between the ridges suggest that internal tide generation for that location can be described with a linear model; nonlinear steepening and rotation are the key factors in modifying the internal tide west of the strait. These results are also proving helpful in planning further measurements under the IWISE program.

RELATED PROJECTS

ONR project – IWISE: Internal Waves in Straits

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